AN INVESTIGATION OF A THREE PHASE INDUCTION MOTOR WITH AN AXIALLY MOVABLE STATOR

BY

J. E BALSON

AN INVESTIGATION OF A THREE PHASE INDUCTION MOTOR WITH AN AXIALLY MOVABLE STATOR

-

J. E. Balson

AN INVESTIGATION OF A THREE PHASE INDUCTION MOTOR WITH AN AXIALLY MOVABLE STATOR

by

John Edward Balson
Lieutenant Commander, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
Electrical Engineering

United States Naval Postgraduate School
Annapolis, Maryland
1951

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE
in
Electrical Engineering

from the
United States Naval Postgraduate School

PREFACE

This thesis subject was suggested by the Navy Department, Bureau of Ships. The purpose was to alter a three phase induction motor so that the stator could be moved axially with respect to the rotor, and to determine the characteristics of the motor for various positions of the stator. It was hoped that a variable speed motor could be obtained by this method.

An ordinary three phase, wound rotor, induction motor was used. No design data was available on the machine, and a major portion of the project was the determination of the machine constants.

It is wished to specifically acknowledge the assistance given by Professor C. V. O. Terwilliger, of the Postgraduate School, and to thank collectively the members of the Electrical Engineering Department of the Postgraduate School for their individual help and counsel.

This work was performed between August 1950 and June 1951 at the U. S. Naval Postgraduate School, Annapolis, Maryland.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS

b	is primary exciting susceptance per phase.
E	effective value of voltage.
E_1	is the primary induced emf per phase.
E_2	is the secondary induced emf per phase, referred to primary.
f	is frequency in cycles per second.
g	is primary exciting conductance per phase.
I	is effective value of current.
I_b	is stator current for blocked rotor test.
I_1	is the primary current per phase.
I_1'	is the part of the primary current due to the secondary current.
I_2	is the secondary current referred to primary side.
I_e	is the primary exciting current per phase.
I_{e+h}	is the power component of exciting current.
I_ϕ	is magnetizing component of exciting current.
K	is a constant.
L	is coefficient of inductance.
N	is number of turns in a winding.
N_1	is synchronous speed in revolutions per minute.
N_2	is speed of rotor in revolutions per minute.
P_1	is power delivered to primary side per phase.
P_2'	is power transferred across air gap to rotor per phase.
P_2	is internal power developed by rotor per phase.

P_b is power input for blocked rotor test.

R_e is equivalent resistance per phase.

R_1 is the primary resistance per phase.

R_2 is the secondary resistance per phase, referred to primary side.

S is the slip of the rotor.

T is the torque in foot pounds.

V_b is impressed voltage for blocked rotor test.

V_1 is primary impressed voltage per phase.

X_1 is the primary leakage reactance per phase.

X_2 is the secondary leakage reactance per phase, referred to primary side.

X_e is the total equivalent reactance per phase.

$(f+w)$ is friction and windage loss.

θ is an angle

μ is permeability.

ϕ is maximum main magnetic flux.

ϕ_1 is maximum total primary flux including leakage.

ϕ_2 is maximum total secondary flux including leakage.

ϕ_{L1} is maximum primary leakage flux.

ϕ_{L2} is maximum secondary leakage flux.

CHAPTER I

INTRODUCTION

There are normally five ways of varying the speed of a polyphase induction motor:

(a) By inserting resistance in the rotor circuit,

(b) By using a stator winding which can be connected for different numbers of poles,

(c) By varying the frequency,

(d) By concatenation, series or cascade connection for two or more motors,

(e) By inserting voltages in the rotor circuit.

Each of these methods has advantages for certain applications, however they also have disadvantages either in the expense of the motor or of the auxiliary equipment required, or in the limitations of speed control acquired.

This thesis was designed to determine the feasibility of another method of speed control by moving the stator axially with respect to the rotor. The theoretical aspects were developed and an induction motor converted so that the stator could be moved axially. The characteristics of this motor were then determined. A wound rotor was used with the terminals short circuited. The rotor could have been the axially movable element, however the stator was selected for mechanical reasons. Also a squirrel cage rotor could have been used in place of the wound rotor.

As detailed in the body of this thesis, some speed control is possible with an induction motor of this type.

For satisfactory performance the iron laminations of the rotor would have to be extended so that there would always be rotor laminations under the stator laminations regardless of the stator axial position. It is pointed out that only the axial length of the rotor laminations are increased and not the axial length of the rotor conductors. It is realized that this would present construction difficulties, however it is believed that this can be accomplished for a squirrel cage rotor without too much trouble.

CHAPTER II

THEORETICAL CONSIDERATIONS

The following is a basic development of the torque equations for a polyphase induction motor. Refer to Figure 1 and 2, which are the equivalent circuit and the vector diagram for a polyphase induction motor. The diagrams and the below vector equations are all on a per phase basis unless indicated otherwise. All parameters are referred to the stator side and sinusoidal voltages and currents are assumed.

$$P_1 = V_1 I_1 \cos \theta_{I_1}^{V_1} \qquad \text{watts per phase}$$

Resolving V_1 into its components,

$$P_1 = (E_1 + I_1 X_1 + I_1 R_1) I_1 \cos \theta_{I_1}^{V_1}$$

$$= E_1 I_1 \cos \theta_{I_1}^{-E_1} + I_1 X_1 I_1 \cos \frac{\pi}{2} + I_1 R_1 I_1 \cos 0$$

$$= E_1 I_1 \cos \theta_{I_1}^{-E_1} + 0 + \text{Stator copper losses}$$

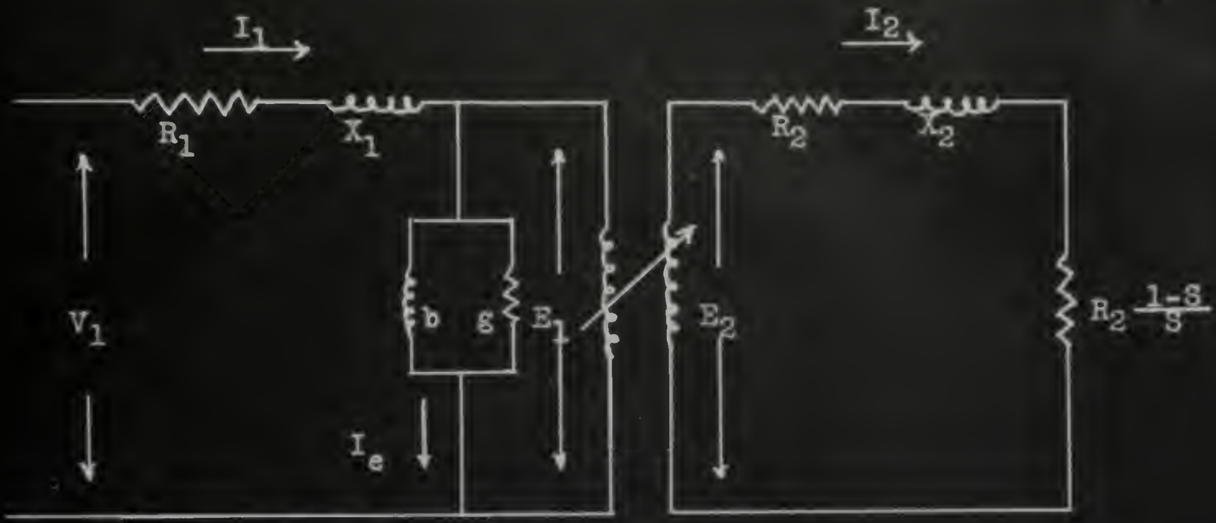
Replacing I_1 by its components,

$$P_1 = E_1 (I_1' + I_\phi + I_{e+h}) \cos \theta_{I_1}^{-E_1} + \text{stator copper losses}$$

$$= E_1 I_1' \cos \theta_{I_1'}^{-E_1} + E_1 I_\phi \cos \frac{\pi}{2} + E_1 I_{e+h} \cos 0$$

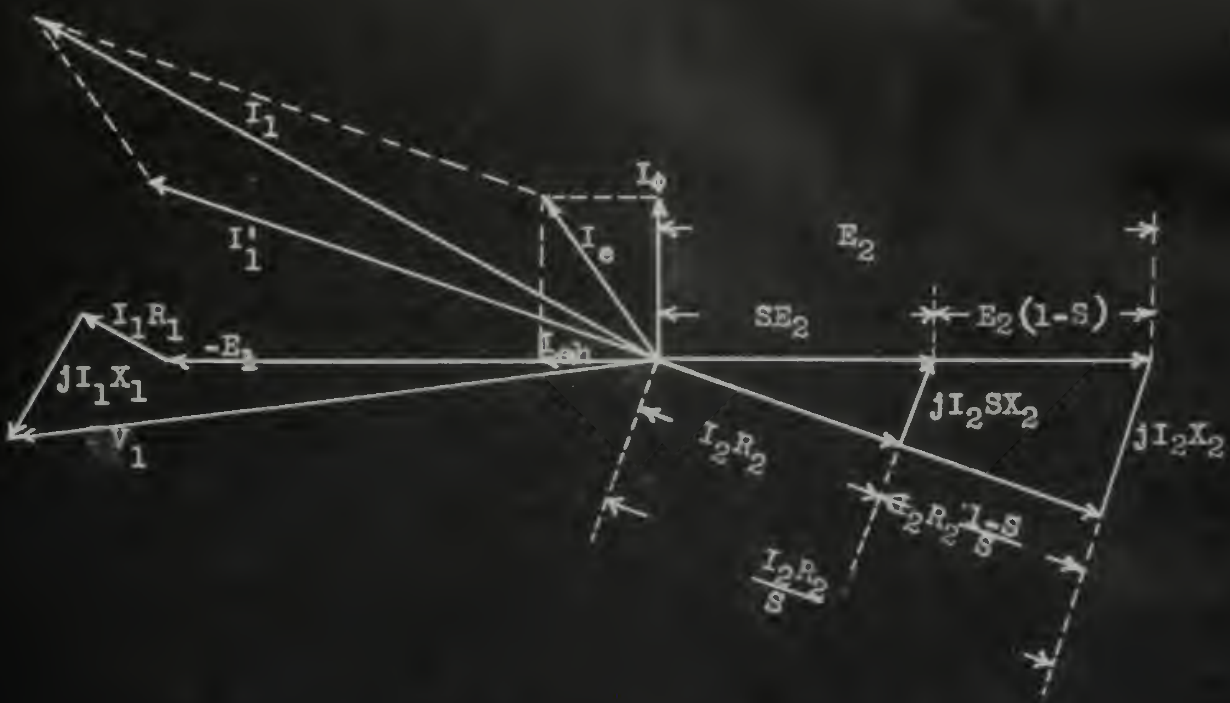
$$+ \text{stator copper losses}$$

$$= E_1 I_1' \cos \theta_{I_1'}^{-E_1} + \text{core loss} + \text{stator copper losses}$$



EQUIVALENT CIRCUIT FOR POLYPHASE
INDUCTION MOTOR

Figure 1.



VECTOR DIAGRAM FOR POLYPHASE INDUCTION MOTOR

Figure 2.

$E_1\ I_1'\ \cos\ \theta_{I_1'}^{-E_1}$ is power transferred across air gap to rotor and is equal to rotor power P_2'.

$$P_2' = E_1\ I_1'\ \cos\ \theta_{I_1'}^{-E_1} \quad \text{watts per phase}$$

$$= E_2\ I_2\ \cos\ \theta_{I_2}^{E_2} \quad \text{watts per phase}$$

Resolving E_2 into its components,

$$P_2' = \left[I_2\ R_2 + I_2\ S\ X_2 + E_2(1-S)\right]\ I_2\ \cos\ \theta_{I_2}^{E_2}$$

$$= I_2^2\ R_2\ \cos\ 0 + I_2^2\ X_2\ S\ \cos\ \frac{\pi}{2} + E_2(1-S)\ I_2\ \cos\ \theta_{I_2}^{E_2}$$

$$= I_2\ E_2(1-S)\ \cos\ \theta_{I_2}^{E_2} + \text{rotor copper loss}$$

$I_2\ E_2(1-S)\ \cos\ \theta_{I_2}^{E_2}$ is internal power developed by rotor and is equal to P_2.

$$P_2 = I_2\ E_2(1-S)\ \cos\ \theta_{I_2}^{E_2} \quad \text{watts per phase}$$

$$I_2 = \frac{E_2\ S}{\sqrt{R_2^2 + S^2\ X_2^2}}$$

$$\cos\ \theta_{I_2}^{E_2} = \frac{R_2}{\sqrt{R_2^2 + S^2\ X_2^2}}$$

$$P_2 = \frac{E_2^2\ (1-S)\ S\ R_2}{R_2^2 + S^2\ X_2^2} \quad \text{watts per phase}$$

$$P_2 = \frac{2\pi N_2\ T\ (746)}{33{,}000} \quad \text{watts per phase}$$

$$N_2 = N_1(1-S)$$

$$P_2 = \frac{2\pi T\ 746\ N_1(1-S)}{33{,}000} \qquad \text{watts per phase}$$

$$T = \frac{33{,}000\ P_2}{2\pi 746\ N_1(1-S)} \qquad \text{foot pounds per phase}$$

$$T = \frac{33{,}000}{2\pi 746\ N_1}\left[\frac{E_2^2\ S\ R_2}{R_2^2 + S^2\ X_2^2}\right] \qquad \text{foot pounds per phase (1)}$$

E_2 corresponds to the voltage induced in the secondary of a static transformer by the mutual flux. E_2 in the above equation is nearly constant for a transformer. However, in an induction motor, due to the increased leakage flux, E_2 is not constant and will vary with load. With this motor, as the stator is pulled away from the rotor, E_2 will decrease considerably due to the high leakage flux.

With a line voltage of 230 volts (phase voltage of 132.8 volts) impressed on the stator, the following rotor phase voltages referred to primary, were measured for various stator positions, with the rotor on open circuit.

Rotor position	V_1(phase voltage)	E_2(phase voltage)
100% Rotor	132.8	132.8
80% Rotor	132.8	129.5
60% Rotor	132.8	121.0
40% Rotor	132.8	103.8
20% Rotor	132.8	82.3

Percent rotor in above column and elsewhere in this thesis means the percent of the total rotor laminations surrounded by stator laminations. The effect of this re-

duction in E_2 can best be observed by reference to equation (1).

$$T = K\frac{E_2^2\ S\ R_2}{R_2^2 + S^2\ X_2^2}$$

Since $S^2\ X_2^2$ is negligible at small slips this equation reduces to

$$T \cong \frac{K\ E_2^2\ S}{R_2}$$

For a given torque, if E_2 is reduced by one-half, S will be increased by about a factor of four. In this motor under normal conditions at full load the slip is about .04. So that reducing E_2 by one-half will increase the slip to .16. This represents a change in speed in the motor tested, from 1152 to 1008 revolutions per minute. Thus, there is some speed control indicated.

Now let us see what effect this change in E_2 and S has on the current I_2. Since E_2 is produced directly by the useful flux furnished by the primary winding and linked with the secondary winding it is a measure of the flux in both magnitude and phase position. The flux in the torque equation may therefore be replaced by E_2, and the equation becomes

$$T = K\ E_2\ I_2 \cos \theta_{E_2}^{I_2}$$

$$I_2 = \frac{S\ E_2}{\sqrt{R_2^2 + S^2\ X_2^2}} \qquad (2)$$

$$\cos \theta^{I_2}_{E_2} = \frac{R_2}{\sqrt{R_2^2 + S^2 X_2^2}}$$

$$T = \frac{K E_2^2 R_2 S}{R_2^2 + S^2 X_2^2} \qquad \text{as before}$$

By referring to equation (2) it is evident that with small slip the value of $S^2 X_2^2$ is negligible, so that equation (2) reduces to

$$I_2 \cong \frac{S E_2}{R_2}$$

This equation indicates that I_2 is almost proportional to the product of E_2 and S. As determined previously, a reduction of E_2 by one-half will increase S by a factor of four. Therefore, the current I_2 will be approximately doubled under these conditions.

The above considerations lead to the conclusion that speed can be controlled by varying E_2 which in turn is varied by moving the stator axially with respect to the rotor. With the machine under test the normal slip at full load is .04, and as shown before, by decreasing E_2 by one-half the slip is increased to .16.

This is not a very great change in speed. However, if the secondary resistance is increased to give a normal full load slip of .15, the slip, when E_2 is reduced by one-half, will be .60. This is a considerable change in speed and can be accomplished by designing the rotor with a higher than normal resistance and to carry double the normal

current. This method of speed control would be inefficient due to the resulting high $I^2 R$ losses. However, speed control and not efficiency is the primary consideration in most variable speed induction motors as the efficiency cannot be higher than (1-S) 100 percent.

The previous considerations have been for the rotor side of the circuit. Now let us see the effect of a reduction of E_2 on the stator side. Refer to Figure 2, the vector diagram. E_2 and $-E_1$ are numerically equal since they are the induced emf in the stator and rotor respectively, due to the main flux. Therefore, if E_2 is reduced, $-E_1$ will be reduced by the same amount. From the vector diagram it is apparent that any reduction in $-E_1$ will be accompanied by an increase in $I_1(R_1 + j X_1)$. This reduction in V_1 is undesirable in respect to both efficiency and power factor. R_1 is a fixed parameter and while X_1 will vary as the stator is moved with respect to the rotor, it will not vary appreciably, as determined by test. It is, therefore, apparent that I_1 will increase considerable with a decrease in E_2. I_1 is the vector sum of I_2 referred to the primary side and I_e, the exciting current. Since I_2 is determined primarily from the motor load, I_e must be increased rapidly with any decrease in E_2 as the stator is pulled away from the rotor.

Another way of viewing this increase in exciting current I_e is that the magnetic path for part of the flux is changed from almost all iron to a path that has a very large air gap,

as the stator is pulled away from the rotor. This results in an increase of reluctance of the magnetic path with a necessary increase in the exciting current.

The exciting current is not a pure sine wave due to the saturation of the iron. Ordinarily this does not greatly effect the solution of the problem by vectors since the exciting current is such a small part of the total stator current. In this case, as the stator is moved away from the rotor, the exciting current becomes the principal part of the stator current, and the stator current is not sinusoidal. This will introduce serious errors in the straight vector solution of the motor problem with the stator pulled very far out.

CHAPTER III

LEAKAGE REACTANCES

Since leakage reactances are a very important factor in the understanding of the characteristics of this induction motor, a separate chapter is being devoted to them.

Reactance in either winding is caused by leakage fluxes which interlink one winding and do not interlink the other. These leakage fluxes consist of various parts as follows:

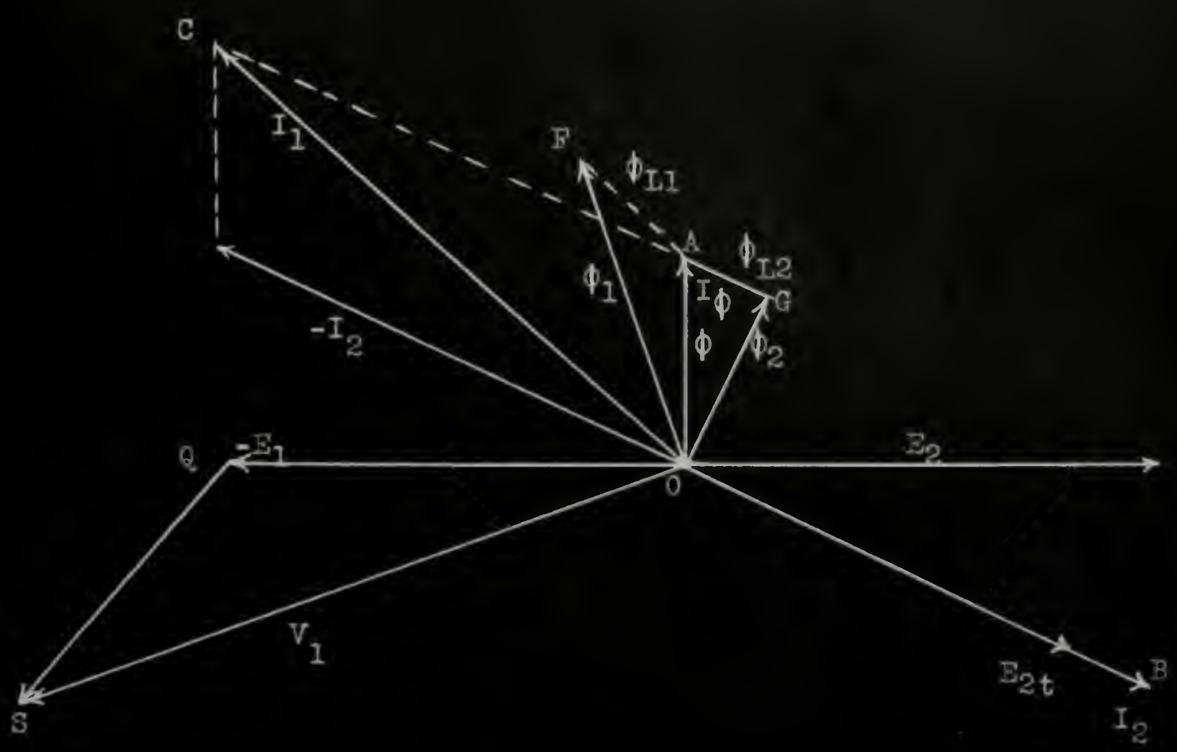
1. Across the stator slots and through the copper.
2. Across the opening above the windings in the stator slots.
3. In the airgap. (zig-zag leakage path)
4. Across the opening above the windings in the rotor slots.
5. Across the rotor slots through the copper.
6. End turn leakage flux.

Each of the leakage fluxes is directly proportional to the current which produces it, since its reluctance is principally in air, for which $\mu = 1$. In the case of the main flux, where the path is through iron the relationship between flux and current is determined by the magnetization curve of the iron used; this is not the case for leakage fluxes.

In general reactance voltage $= 2\pi f L I = I X$ and lags 90° behind the current, since the current is in phase with the magnetic flux produced by the current and emf lags 90° behind the magnetic flux. The emf lags 90° behind the

magnetic flux, as it is proportional to the rate of change in flux; thus it is zero when the magnetism is at its maximum value, and a maximum when the flux passes through zero, where it changes quickest.

One way of viewing the relationship of leakage fluxes and the main flux is shown in Figure 3 which is a combination mmf diagram and current diagram. For simplicity I_{e+h} and R_1 are assumed zero. O A is the reactive component I_ϕ of the magnetizing current which produces the main flux ϕ. O B is the rotor current and O C is the stator current which is equal to the vector sum of I_ϕ and $-I_2$. The main flux ϕ is in phase with the current I_ϕ. The scale of the flux vector is so selected that O A is equal to ϕ. The primary leakage flux ϕ_{L1} is proportional to the stator current and parallel to I_1. The rotor leakage flux ϕ_{L2} is proportional to the secondary current and parallel to I_2. From the diagram O F is total primary flux ϕ_1 and O G is total secondary flux ϕ_2. The counter emf produced by the main flux ϕ is perpendicular to ϕ and is represented by O Q. To the counter emf is added the voltage $QS = I_1 X_1$ necessary to overcome the emf due to the leakage flux Q_{L1} of the primary winding. $QS = I_1 X_1$ is perpendicular to I_1 and leads I_1 by 90^o. O S is the primary terminal voltage V_1. O S is perpendicular to $OF = \phi_1$ since ϕ_1 is the total primary flux. Correspondingly E_{2t} is perpendicular to total secondary flux $\phi_2 = OG$. E_{2t} is in phase with I_2 because a pure ohmic resistance in the external circuit represents the mechanical power of the rotor.



COMBINATION MMF AND CURRENT DIAGRAM

Figure 3.

CHAPTER IV

MOTOR CHARACTERISTICS FOR VARIOUS ROTOR POSITIONS

The motor was loaded with a prony brake at various values of torque and for various rotor positions. The torque was measured with a platform scale and the speed was measured with a Jagabi Indicator. Current, slip, power factor, and efficiency are plotted versus torque for various values of rotor position and are given in Figures 4, 5, 6, and 7. Percent rotor in these diagrams means the percent of rotor laminations surrounded by stator laminations.

1. Current, Figure 4

As is expected, the rotor current goes up very fast as the stator is pulled away from the motor. This increase in current is primarily due to the increased magnetizing current which is due to the increase in reluctance of the magnetic path.

2. Slip, Figure 5

As was shown in Chapter I, the slip will increase as the stator is pulled away from the rotor. The slip at full load with the stator in normal position is about .04. With the stator pulled 80 percent of the way out the slip is increased to .097.

3. Power Factor, Figure 6

The power factor is determined by the ratio of the active component of the primary current to the total primary current. The primary current is equal to the sum of the squares of the active and reactive components. The power factor, there-

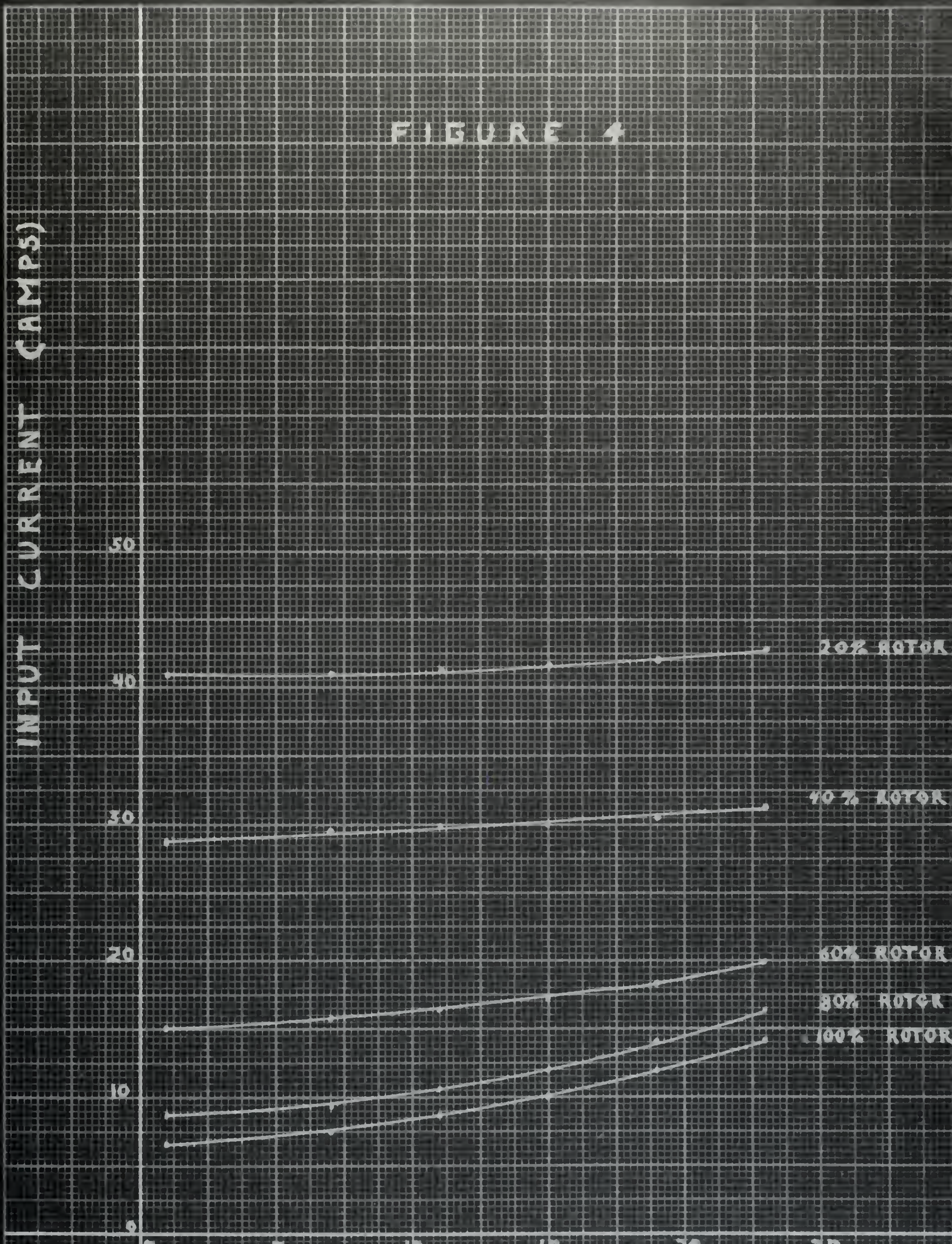


FIGURE 4
INPUT CURRENT (AMPS)
TORQUE (FT. LBS)
20% ROTOR
40% ROTOR
60% ROTOR
80% ROTOR
100% ROTOR
0
10
20
30
40
50
5
15
25

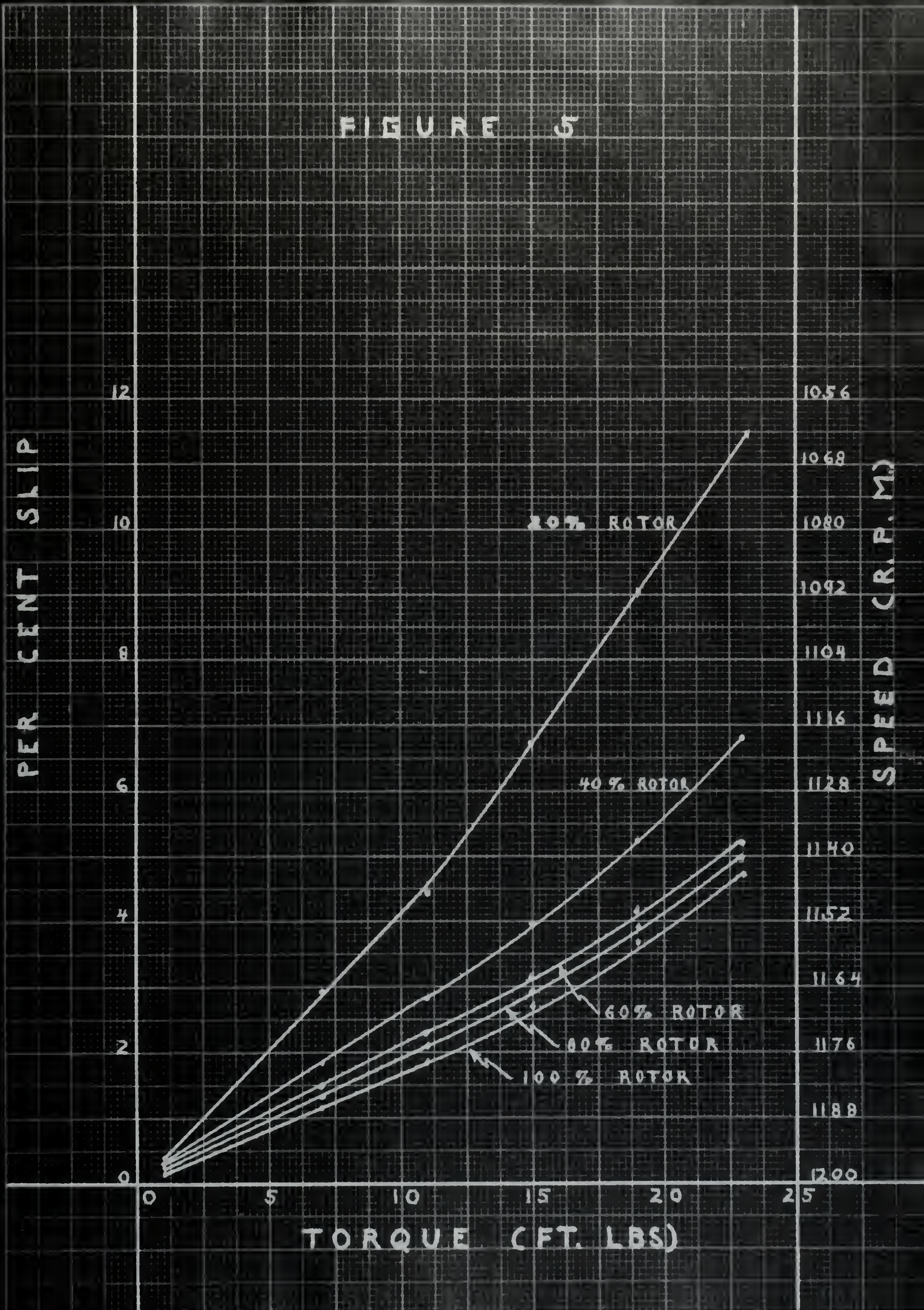


FIGURE 5
PER CENT SLIP
SPEED (R.P.M.)
TORQUE (FT. LBS)
20% ROTOR
40 % ROTOR
60% ROTOR
80% ROTOR
100 % ROTOR
0
2
4
6
8
10
12
5
15
20
25
1056
1068
1080
1092
1104
1116
1128
1140
1152
1164
1176
1188
1200

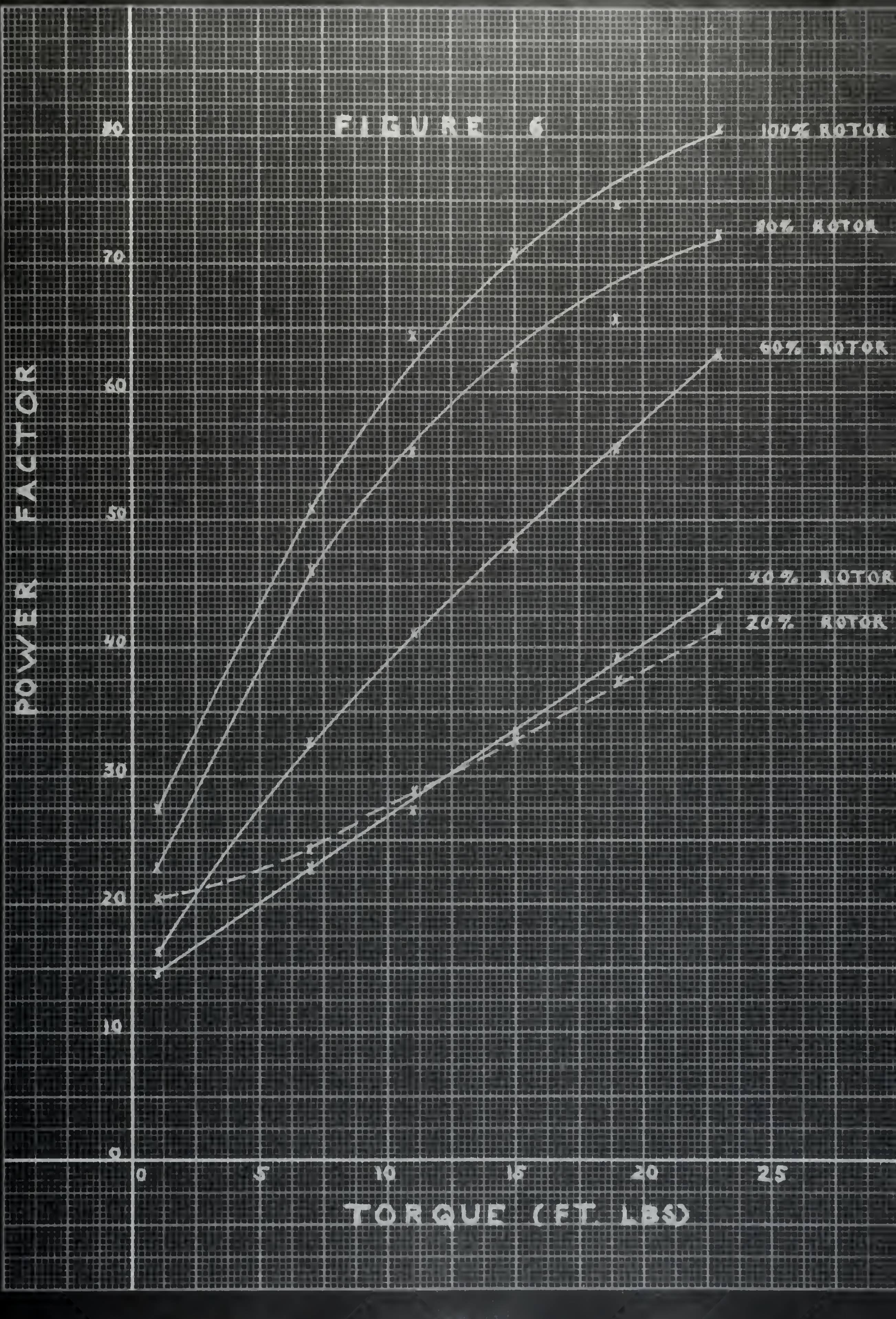


FIGURE 6
100% ROTOR
80% ROTOR
60% ROTOR
40% ROTOR
20% ROTOR
POWER FACTOR
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
TORQUE (FT. LBS)

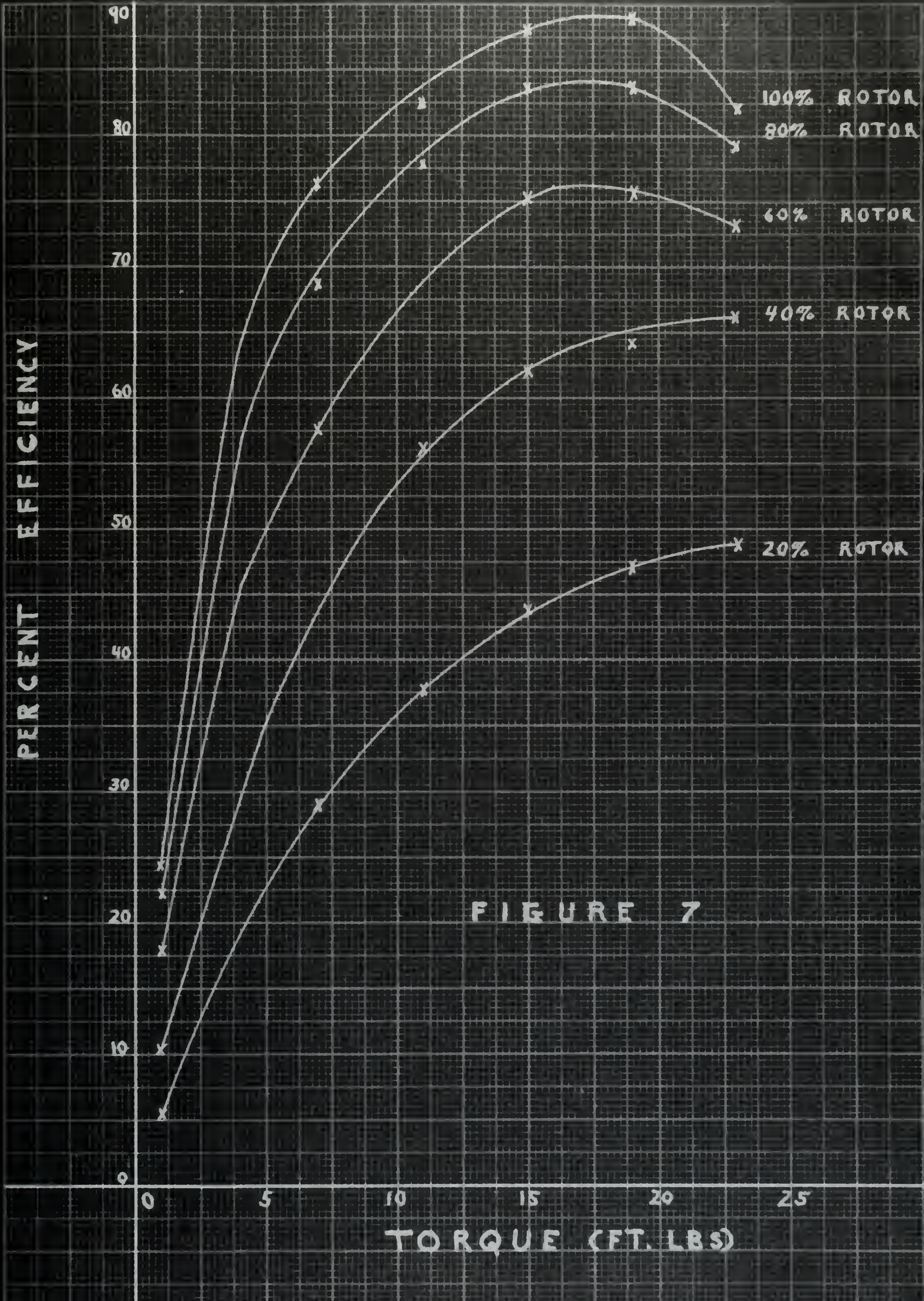

PERCENT EFFICIENCY
TORQUE (FT. LBS)
100% ROTOR
80% ROTOR
60% ROTOR
40% ROTOR
20% ROTOR
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25

FIGURE 7

fore, is reduced for an increase in the reactive component of the current. The reactive component consists of two parts, one part the reactive magnetizing current I_ϕ and the other part due to the leakage fluxes. The reactive magnetizing current depends on the length of the air gap and the nature of the iron. In the case of this motor, as the stator is pulled away from the rotor the air gap is increased and leakage reactance is increased. Therefore, it is to be expected that the power factor decreases as the stator is pulled away from the motor and this is the case as found by actual test, as shown in Figure 6.

4. Efficiency, Figure 7

The decrease in efficiency as shown in Figure 7 is due primarily to the increased copper losses caused by the increase in magnetizing current. Another factor that decreases the efficiency is the increase in core loss due to the increase in flux density at the end of the rotor under the stator due to fringing.

CHAPTER V

DETERMINATION OF CONSTANTS FOR EQUIVALENT CIRCUIT

1. Reactances

The blocked rotor test is the normal method of determining the equivalent reactance X_e of an induction motor. If P_b is the power input with rotor blocked and V_b and I_b are the corresponding impressed voltage and stator current, the equivalent reactance of the entire motor at primary frequency is

$$X_e = \frac{V_b}{I_b} \sqrt{1-(\text{blocked power factor})^2} \quad (3)$$

It is customary to assume that X_e divides equally between X_1 and X_2. This assumption is not necessarily correct, but it will not effect the calculated performance of the motor so far as torque and output are concerned.

The blocked rotor test usually is made at reduced voltage V_b in order to keep the current at a reasonable value. The determination of locked current at rated voltage V_1 by multiplying the tested current I_b by $\frac{V_1}{V_b}$ may yield a value that is smaller than would be obtained by applying rated voltage. This is due to the fact that saturation is not reached at the reduced voltage. The influence of saturation in the leakage paths occurs only at high current (high slip). At normal current there is no saturation in the leakage paths. Therefore, when calculating the performance of the motor at light load the non-saturated leakage

reactances should be used and when calculating the performance at high loads the saturated leakage reactance should be used.

The equation for equivalent reactance (3) ignores I_e, the primary exciting current shown in Figure 1. This is normally a reasonable assumption since the impedance of the exciting current branch is high in comparison to the rest of the circuit. Also, under blocked conditions the flux is small, so the core loss may be neglected, the wattmeter readings thus corresponding to the copper losses in primary and secondary. However, as the stator is pulled away from the rotor, the above assumption is no longer valid and serious errors seem probable.

The following values of equivalent reactance were obtained for various stator positions at an impressed line voltage of 113 volts and 45 volts.

Equivalent Reactance (ohms)

stator position	E_L 113 volts	E_L 45 volts
100% rotor	2.14	2.28
80% rotor	2.05	2.22
60% rotor	2.03	2.20
40% rotor	2.16	2.29
20% rotor	2.24	2.38

These values indicate a fairly constant value for equivalent reactance regardless of stator position.

2. Resistances.

The primary and secondary resistances were measured with

a Kelvin Double Bridge and found to be .368 and .501 ohms respectively. These values are ohmic resistances at 25° C., and the secondary resistance is referred to the primary side. The equivalent resistance per phase is determined from the blocked rotor test.

$$R_e = \frac{P_b}{I_b^2} \cong R_1 + R_2$$

If the effective resistances of the stator and rotor are assumed to be in the same ratio as the ohmic resistances, the effective resistances of the stator and rotor can be found by dividing the equivalent resistance of the motor into two parts which are proportional to the ohmic resistances of the stator and rotor. Using this method the effective resistance of the stator was found to be .494 ohms at 25° C. The effective resistance of the rotor is practically the same as the ohmic resistance for small values of slip.

In order to refer the rotor resistance to the stator side the actual rotor resistance is multiplied by the turns ratio squared. The effective turns ratio was determined by applying reduced voltage to the stator and measuring the induced voltage on the open rotor terminals. The turns ratio was found to be 2.98, being step down from the stator to the rotor.

3. Exciting admittance.

The exciting current conductance and susceptance are normally determined by a no load test as follows:

$$P_N = P_1 - \text{copper losses} - (f+w)$$

$$I_{e+h} = \frac{P_n}{V_1}$$

$$I_\phi = I_1 \sqrt{1-(\text{no load power factor})^2}$$

$$g = \frac{I_{e+h}}{V_1}$$

$$b = \frac{I_\phi}{V_1}$$

The above solution is only correct when the voltage drop on the stator side is negligible. This assumption is not valid for this motor due to the high exciting current and resulting voltage drop on the primary side. It was, therefore, decided to solve directly the equivalent "T" circuit using values for X_1 and X_2 of 1.07 ohms. Using this method the below values were found for g and b for various stator positions.

Stator Position	g	b
100% rotor	.0029	.0512
80% rotor	.0040	.0637
60% rotor	.0056	.134
40% rotor	.0101	.290
20% rotor	.0312	.495

4. Friction and Windage.

Friction and windage were determined as shown in Figure 8. The motor was run at no load with the stator in the normal

position and at various impressed voltage from 282 to 53 volts. The total power input was then plotted against the impressed voltage, and the power curve extended to the vertical axis. The intersection with the vertical axis gives the total friction and windage losses since at that point the core and copper losses are zero. By this method the friction and windage losses were found to be 175 watts.

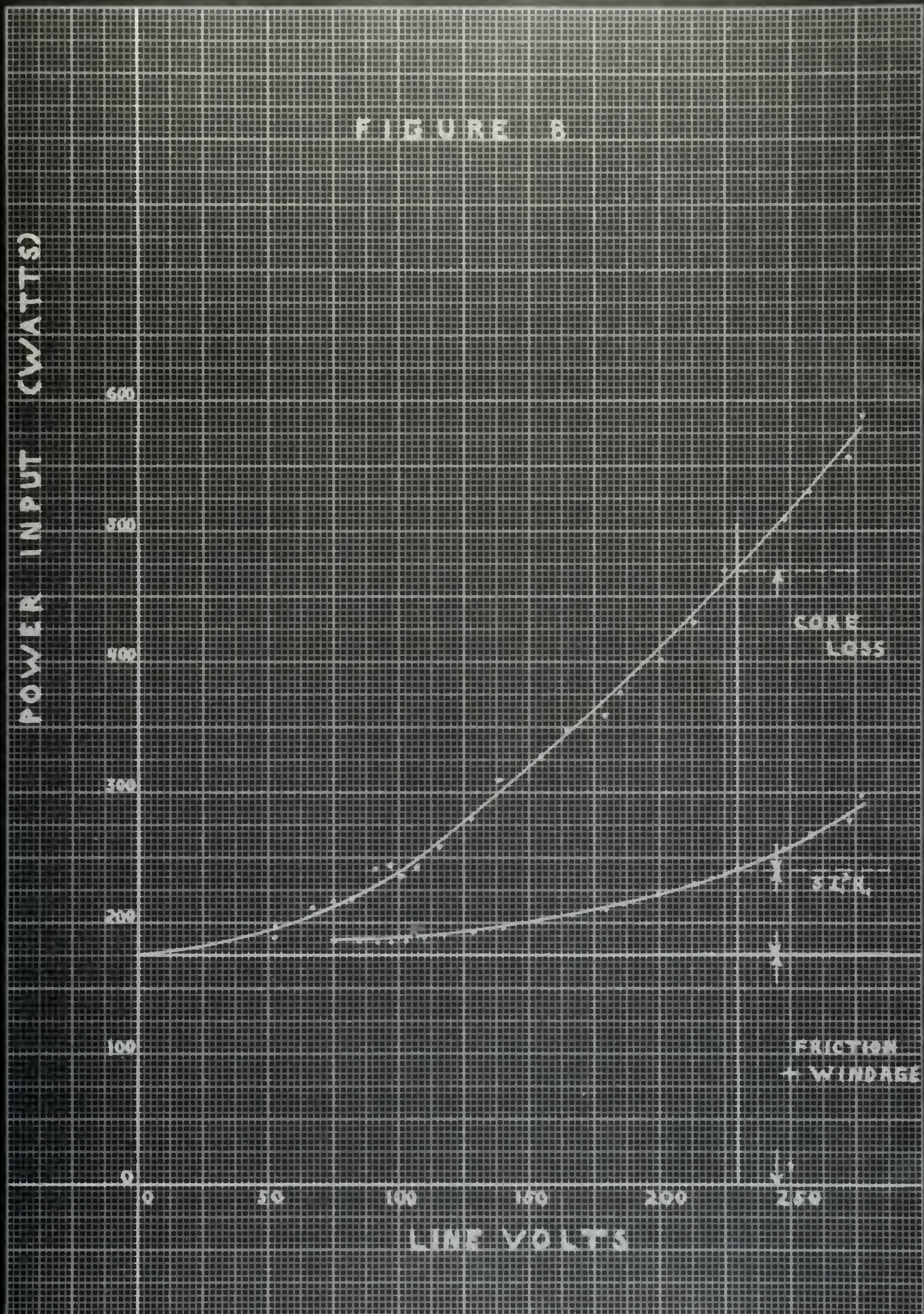


FIGURE 8
POWER INPUT (WATTS)
600
500
400
300
200
100
0
0
50
100
150
200
250
LINE VOLTS
CORE LOSS
I^2R
FRICTION + WINDAGE

CHAPTER VI

CONCLUSIONS

1. Electrical

It is readily apparent that an axially movable stator on a normal induction motor will give a slight speed variation and a great increase in primary current. The main cause of the high current is the increase in exciting current as the stator is moved away from the rotor.

However, by a few design changes it would be possible to construct a variable speed induction motor by this method. These design changes are:

a. Use a squirrel cage rotor with the laminations extended beyond the rotor conductors so that the iron rotor laminations are always under the stator laminations regardless of the position of the stator. This will reduce magnetizing current to the normal value.

b. A higher than normal rotor resistance so that the slip with full load and the stator in normal position will be about .10. This will greatly magnify the changes in slip as the stator is pulled away from the rotor.

2. Mechanical

It would make no difference electrically whether the rotor or stator were the axially movable element. However, from mechanical considerations it would be simpler to have the stator be the movable element.

The air gap clearance of an induction motor is made as small as possible, being determined largely by mechanical

considerations. With a motor of this type the rotor shaft of necessity is longer than normal which means that the rotor shaft would have to be of heavier construction than normal. If the stator is the movable element it must be kept rigidly in place and kept in very accurate axial alignment in order to keep the air gap uniform.

BIBLIOGRAPHY

1. Bryant, J. M. and E. W. Johnson. Alternating current machinery. New York, McGraw-Hill, 1935.

2. Lawrence, R. R. Principles of alternating current machinery. New York, McGraw-Hill, 1940.

3. Department of Electrical Engineering, Massachusetts Institute of Technology. Magnetic circuits and transformers. New York, John Wiley and Sons, 1943.

4. Liwschitz-Garik, M. and C. C. Whipple. Electric machinery, Vol. II. New York, D. Van Nostrand, 1946.

5. Still, A. Elements of electrical design. New York, McGraw-Hill, 1932.

APPENDIX A

DATA

Running Light Test

$R_1 = .494$ ohms

$X_1 + X_2 = 1{,}14$ ohms

% rotor	I_1 amperes	E_1 volts	P_1 watts	g mhos	b mhos
100.	6.51	230.	354.	.00294	.0512
80.	7.90	230.	462.	.00401	.0637
60.	15.3	230.	747.	.0056	.134
40.	28.7	230.	1685.	.0101	.290
20.	41.0	230.	3300.	.0312	.494

g and b solved by equivalent circuit, figure 1

Blocked Rotor Test

% rotor	I_b amperes	E_b volts	P_b watts	cos	X_e ohms	X_1 X_2 ohms	R_e ohms
100.	27.4	113.	2344.	.4375	2.14	1.07	1.04
100.	10.3	45.	342.	.428	2.28	1.14	1.07
80.	28.5	113.	2472	.443	2.05	1.03	
80.	10.6	45.	355.	.429	2.22	1.11	
60.	28.95	113.	2428.	.428	2.03	1.02	
60.	10.7	45.	352.	.421	2.20	1.10	
40.	27.7	113.	2132.	.393	2.16	1.08	
40.	10.4	45.	325.	.401	2.29	1.15	
20.	27.1	113.	1900.	.359	2.24	1.12	
20.	10.1	45.	281.	.375	2.38	1.19	

$$X_e = \frac{V_b}{I_b}\sqrt{1-(\text{blocked power factor})^2}$$

$$\cong X_1 + X_2$$

$$R_e = \frac{P_b}{3I_b^2} \cong R_1 + R_2$$

Friction and Windage Test

$R_1 = .494$ ohms

rpm	E_1 volts	I_1 amperes	P_1 watts	$3 I_1^2 R_1$
1197.	282.	9.3	590.	128.
1196.	272.	8.5	555.	107.
1196.	257.	7.9	530.	93.
1195.	247.	7.35	510.	80.
1195.	226.	6.55	470.	63.
1194.5	212.	6.15	430.	56.
1194.	200.	5.60	400.	46.
1191.	186.	5.20	378.	40.
1190.5	179.	4.85	358.	35.
1189.	168.	4.50	347.	30.
1188.	155.	4.15	327.	26.
1188.	139.	3.90	310.	22.
1187.	128.	3.40	279.	17.
1186.	118.	3.25	253.	15.
1184.5	108.	3.10	241.	14.
1183.	103.	3.00	228.	13.
1179.	97.	2.85	245.	12.
1179.	92.	2.75	243.	11.
1174.5	82.5	2.60	216.	10.
1170.	75.5	2.60	216.	10.
1162.5	67.	2.70	212.	11.
1139.	53.	3.15	198.	14.

Load Runs

100% Rotor $V_1 = 230$ volts(line)

I_1 amperes	input watts	torque Ft. lbs.	r.p.m.	power factor	output watts	efficiency per cent	slip
6.5	710.	1.	1198.	.274	175.	24.5	.00167
7.6	1540.	7.	1186.	.509	1178.	76.4	.01167
8.7	2230.	11.	1177.5	.645	1840.	82.5	.01875
10.0	2830.	15.	1167.5	.710	2490.	87.9	.0271
11.8	3500.	19.	1156.5	.746	3120.	89.1	.0363
14.2	4550.	23.	1144.	.807	3740.	82.3	.0467

80% Rotor

8.7	780.	1.	1197.5	.225	175.	22.4	.00208
9.3	1710.	7.	1184.	.462	1176.	68.7	.01333
10.7	2360.	11.	1175.	.554	1837.	77.8	.0208
12.1	2970.	15.	1165.	.617	2485	83.7	.0292
14.1	3720.	19.	1153.	.658	3115.	83.7	.0391
16.3	4700.	23.	1141.5	.725	3735.	79.4	.0487

60% Rotor

15.2	980.	1.	1197.	.162	175.	17.9	.00251
15.8	2050.	7.	1182.5	.327	1175.	57.4	.0146
16.3	2680.	11.	1172.	.412	1830.	68.4	.0233
17.3	3290.	15.	1162.	.478	2480.	75.4	.0317
18.4	4100.	19.	1150.	.559	3100.	75.6	.0417
19.7	4950.	23.	1138.5	.632	3720.	73.2	.0513

Load Runs

40% Rotor

I_1 amperes	input watts	torque ft. lbs.	r.p.m.	power factor	output watts	efficiency per cent	slip
28.7	1685.	1.	1196.5	.148	175.	10.3	.00292
29.5	2670.	7.	1177.5	.227	1170.	43.8	.01875
29.8	3230.	11.	1165.5	.272	1818.	56.2	.0287
30.0	3960.	15.	1152.5	.331	2460.	62.2	.0396
30.5	4780.	19.	1137.0	.394	3070.	64.2	.0525
31.3	5500.	23.	1118.5	.442	3650	66.3	.0679

20% Rotor

I_1 amperes	input watts	torque ft. lbs.	r.p.m.	power factor	output watts	efficiency per cent	slip
40.9	3300.	1.	1195.	.203	175.	5.3	.00417
41.0	3960.	7.	1164.5	.243	1158.	29.2	.0296
41.2	4750.	11.	1146.5	.289	1790.	37.7	.0446
41.5	5440.	15.	1119.5	.329	2380.	43.8	.0671
42.0	6280.	19.	1092.	.376	2950.	47.0	.0900
43.0	7120.	23.	1063.	.416	3480.	48.8	.1142

note; torque and output include friction and windage.

NAME PLATE DATA

5 KVA	60 cycles
110-220 Volts	1200 RPM
26-13 Amps.	S. O. 47E551
90% P. F.	Serial 4864608
1-3-6 Phase	

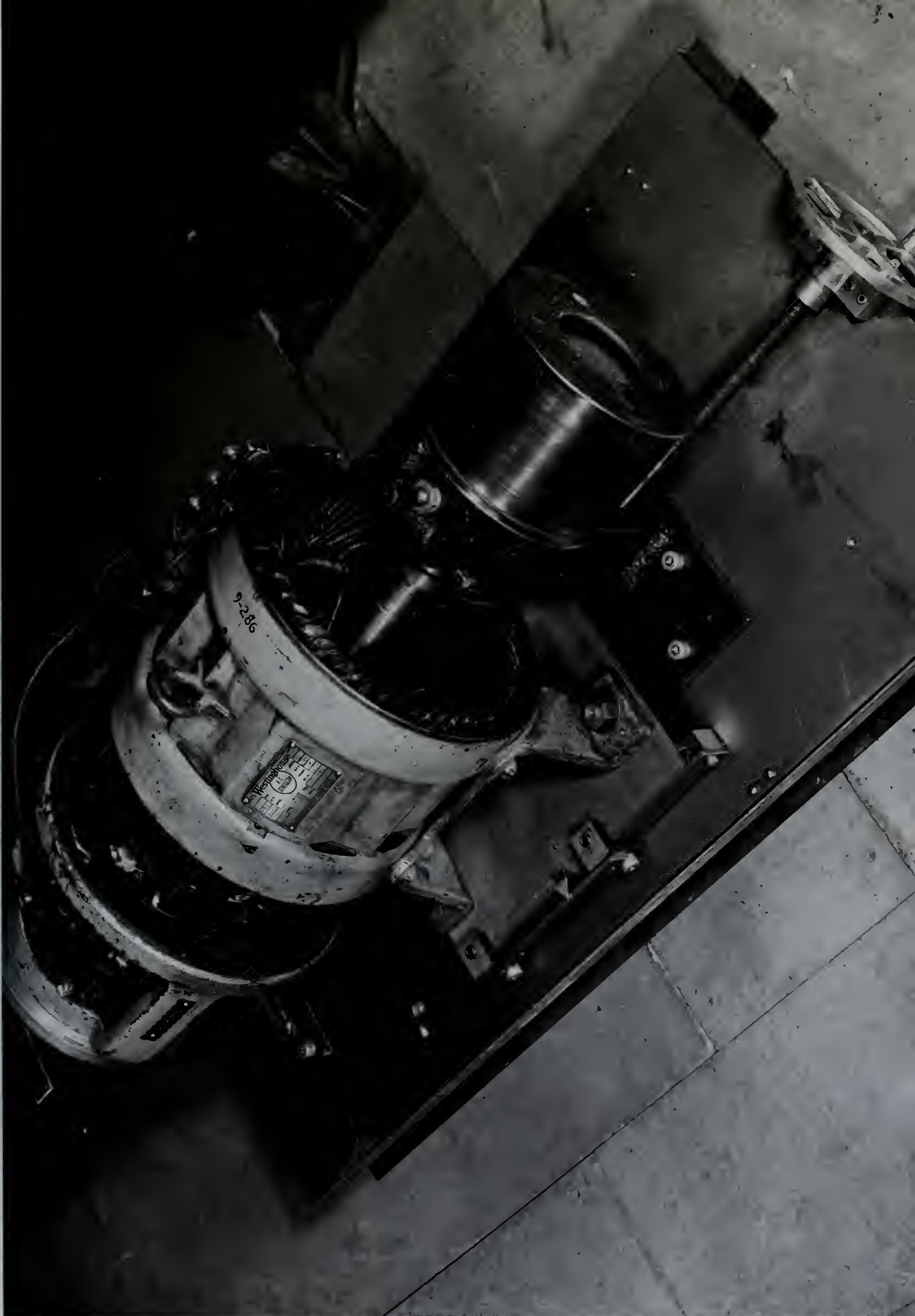
Westinghouse Electric and Manufacturing Company,

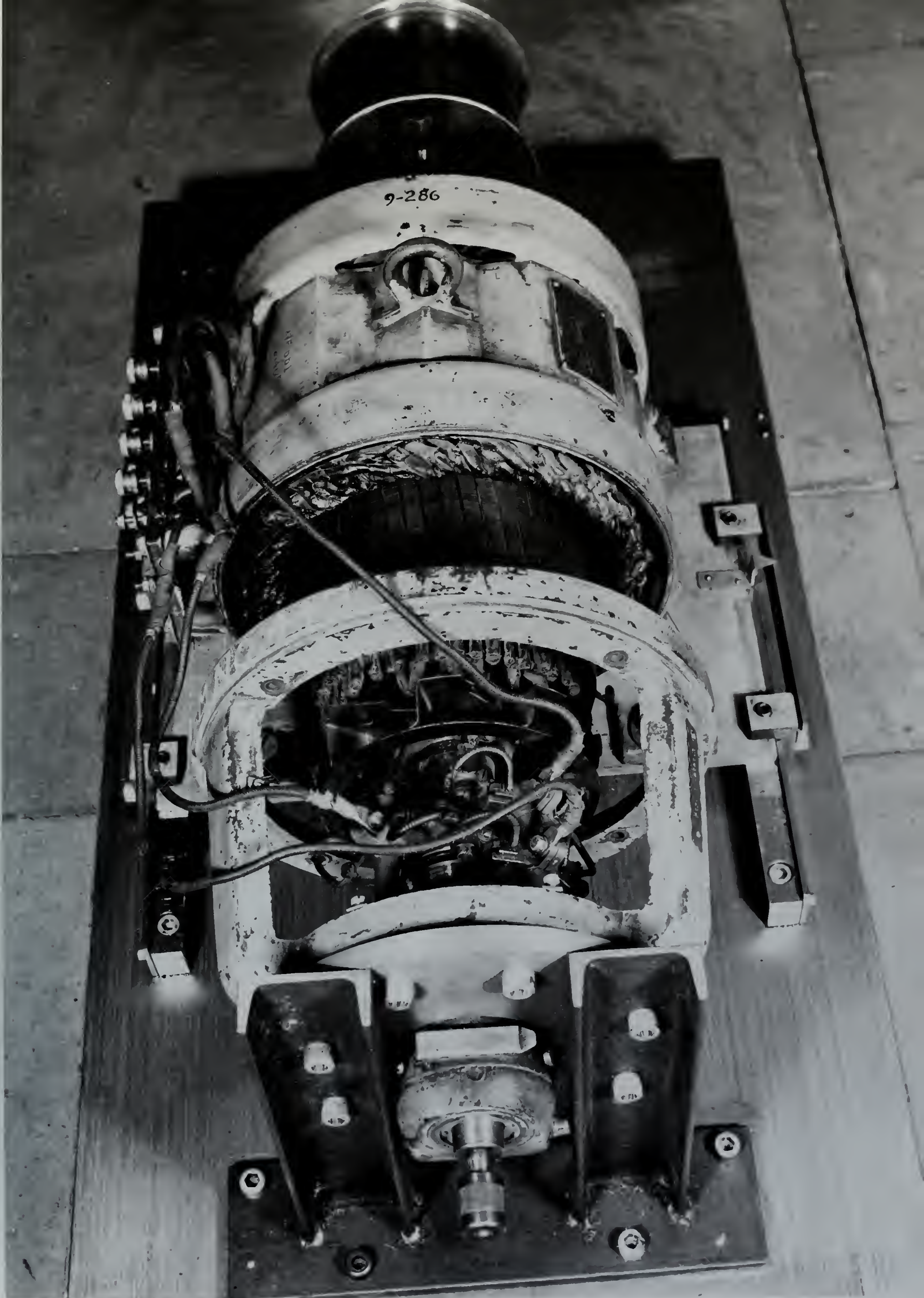
East Pittsburgh Works,

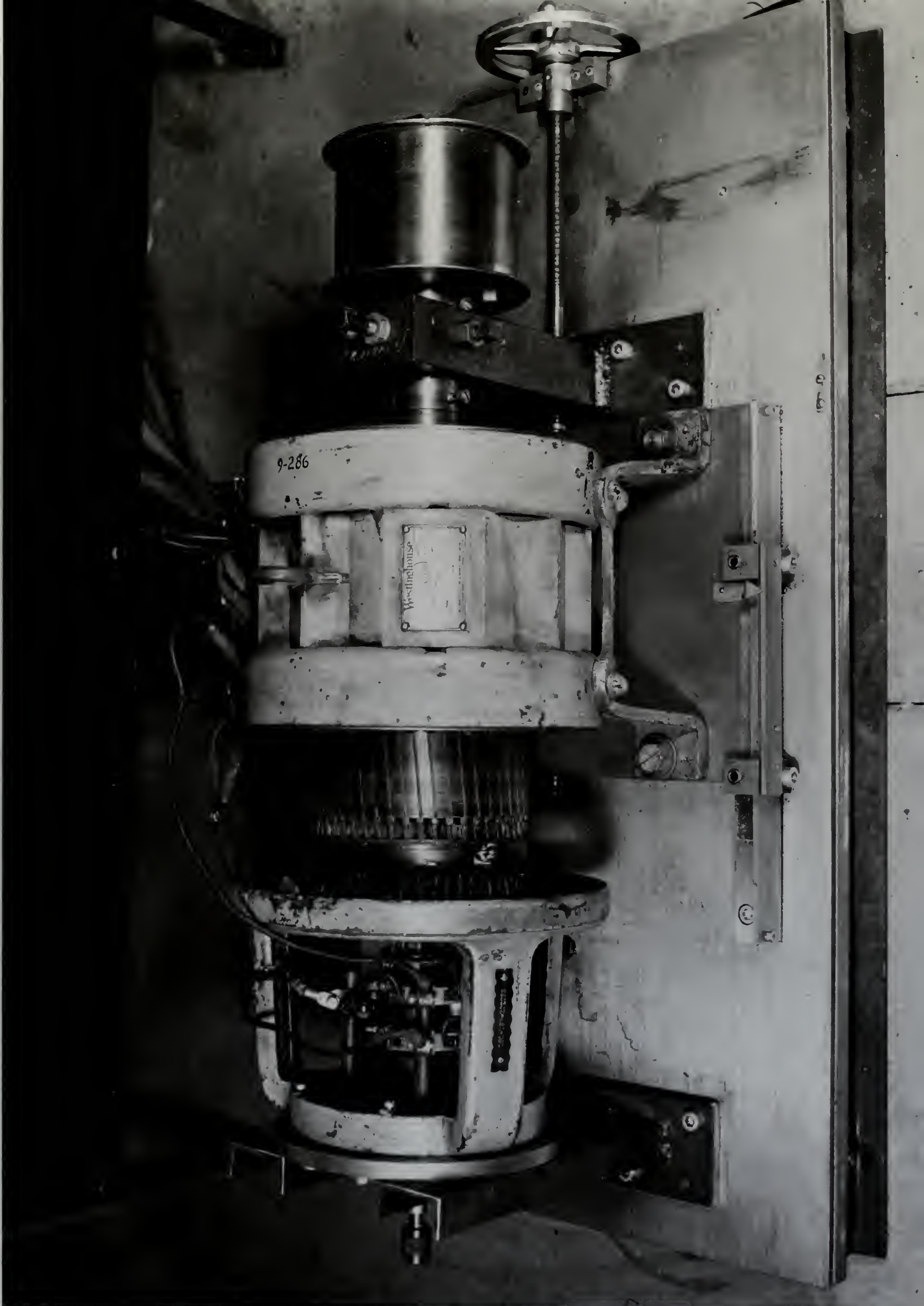
East Pittsburgh, Pa. U. S. A.

APPENDIX B

PHOTOGRAPHS OF EQUIPMENT


9-286
Westinghouse


9-286


9-286
Westinghouse

Thesis 15566
B204 Balson
c.1 An investigation of
a three phase induction
motor with an axially
movable stator.